He-like argon, chlorine and sulfur spectra measurement from an Electron Cyclotron Resonance Ion Trap

M Trassinelli[1,2]**, S Boucard**[2]**, D S Covita**[3]**, D Gotta**[4]**, A Hirtl**[5]**,
P Indelicato**[2]**, É-O Le Bigot**[2]**, J M F dos Santos**[3]**, L M Simons**[6]**,
L Stingelin**[6]**, J F C A Veloso**[3]**, A Wasser**[6] **and J Zmeskal**[5]

[1]Gesellschaft für Schwerionenforschung, Darmstadt, Germany
[2]Laboratoire Kastler Brossel, Unité Mixte de Recherche du CNRS n° 8552, Université Pierre et Marie Curie, Paris, France
[3]Physics Department, University of Coimbra, Portugal
[4]Institut für Kernphysik, Forschungszentrum Jülich, Jülich, Germany
[5]Stefan Meyer Institut für Subatomare Physik, Vienna, Austria
[6]Paul Scherrer Institut, Villigen PSI, Switzerland

E-mail: m.trassinelli@gsi.de

Abstract. We present a new measurement on X-ray spectroscopy of multicharged argon, chlorine and sulfur obtained with the Electron Cyclotron Resonance Ion Trap installed at the Paul Scherrer Institut (Villigen, Switzerland). For this purpose, we used a crystal spectrometer with a spherically bent crystal having an energy resolution of about 0.4 eV. High intensity $K\alpha$ X-ray spectra were obtained from ions with one $1s$ hole ranging from almost neutral to heliumlike charge states. In particular we observed the $1s2s\,^3S_1 \rightarrow 1s^2\,^1S_0$ M1 and $1s2p\,^3P_2 \rightarrow 1s^2\,^1S_0$ M2 transitions in He-like argon, chlorine and sulfur with unprecedented statistics and resolution. The preliminary analysis presented here describes a new technique to measure precisely energy differences between transitions using a Johann-type Bragg spectrometer. A recent characterization of the spectrometer will allow for a drastic reduction of the systematic errors.

1. Introduction

An Electron Cyclotron Resonance Ion Trap (ECRIT) has been set up at the Paul Scherrer Institut (PSI) in order to produce narrow X-ray lines for a high accuracy determination of the response function of a Bragg crystal spectrometer in the range of 2-4 keV [1]. Such a measurement is crucial for the ongoing pionic hydrogen experiment at PSI [2]. For low- and medium-Z atoms, X-rays from hydrogen-like ions and M1 X-rays from helium-like ions have an energy of a few keV with a natural width in the order of 1 meV or less. Because the kinetic energy of the ions is below 1 eV in such devices [3, 4], a Doppler broadening of less than 40 meV can be expected for transitions in the 3 keV energy range in He-like argon which is negligible compared to the experimental resolution of 0.4 eV. Once calibrated, such a spectrometer allows for precise measurements of highly charged ions to test Quantum Electrodynamics in strong Coulomb fields and the study of the electron-electron interaction in the relativistic regime. In this article we present a recent measurement of atomic spectra of argon, chlorine and sulfur.

In particular we present a preliminary evaluation of the He-like argon and sulphur transition energies.

2. Experimental set-up

The experimental set-up is composed principally by two parts: the ECR ion trap (the X-ray source) and the Bragg spectrometer set-up in a Johann geometry [5]. Various silicon and quartz crystals have been used in order to adjust a suitable Bragg angle for the different measured energy ranges. The crystals are disks of 100 mm in diameter having a thickness of 0.2–0.3 mm. They are spherically bent to a radius of curvature of about 2985 mm by optical attachment to high-quality spherical lenses. The X-rays reflected by the crystal are recorded by a two-dimensional position-sensitive detector placed in proximity of the Rowland circle of the spectrometer. The detector consists of an array of 6 charged coupled devices (CCD) of 600×600 pixels each, with an energy resolution of 140 eV at 3 keV [1, 6, 7]. The ECRIT consists of the pair of superconducting magnets of the cyclotron trap [8], of an AECR-U style permanent hexapole magnet, and of a 6.4 GHz power regulated emitter. Together with special iron inserts, one of the highest mirror ratio (4.5) for ECR sources is achieved. More details can be found in Refs. [1, 9, 10].

3. Data acquisition and analysis

In order to obtain X-ray spectra from highly-charged argon, chlorine and sulfur the gases Ar, $CHClF_2$ and SO_2 were injected. To improve the ionization efficiency, we used a gas mixture with O_2 adjusted to a mixing ratio of about 1:9 (main gas : oxygen gas) with a total pressure in the plasma chamber of $(3-4) \times 10^{-7}$ mbar. In order to identify the different charge states, we used as an initial reference the $K\alpha$ or $K\beta$ lines of the neutral gas. The spectrometer was then moved to the region of the nearby $1s2s\ ^3S_1 \rightarrow 1s^2\ ^1S_0$ M1 transition in the He-like ion. Then the different ECRIT and spectrometer parameters were optimized in order to maximize the M1 line intensity in the detector. The typical illumination time of the CCDs before readout was 30 s. Due to the large intensity of the X-rays, double hits for pixels around the line peak occurred with significant probability. In order to reduce this effect and improve on the peak-to-background ratio, a densimet® collimator was inserted at a distance of 150 mm from the center of the plasma leaving an aperture of 28 mm (horizontal) × 4 mm (vertical) or 28 mm × 1 mm. The measurement of the energy difference between two lines is obtained by measuring the position difference on the CCD plane. However, the energy range of the spectra simultaneously detectable is limited to some tens of eV due to the finite width of the collimator. To access a wider range, the crystal-ECRIT and crystal-detector angles had to be changed. More details about the spectra construction may be found elsewhere [11]. The line positions on the CCD array are measured by fitting the one-dimensional spectrum, obtained from the projection of the two-dimensional pattern to the x-axis, the axis of dispersion. The line shapes are fitted with the theoretical response function of the spectrometer convoluted with a Gaussian distribution. The response function is obtained from Monte Carlo simulations [1], which takes into account the experimental geometry and the rocking curve. The rocking curve of the crystal is obtained from a theoretical calculation performed with the XOP code [12]. The convolution with an additional Gaussian enables to cope with the imperfections of the crystal. The energy values for the measured He-like transitions are given in Table 1. The argon and the sulphur spectra were obtained with a Quartz (10.$\bar{1}$) and Quartz (10.0) crystals, respectively. The error includes the statistical and systematic contributions. The systematic error is due to the accuracy of the detector-crystal distance and the defocalisation of the lines in the detector plane [11]. Our results confirm previous measurements of He-like argon and sulphur using X-ray spectroscopy [19, 21], which have a typically error of about ten times larger than achieved here. They are confirmed by the direct UV measurements of the $2\ ^3P_2 \rightarrow 2\ ^3S_1$ transition [18, 20], which are characterized by an accuracy being one order of magnitude higher than X-ray spectroscopy. Our results
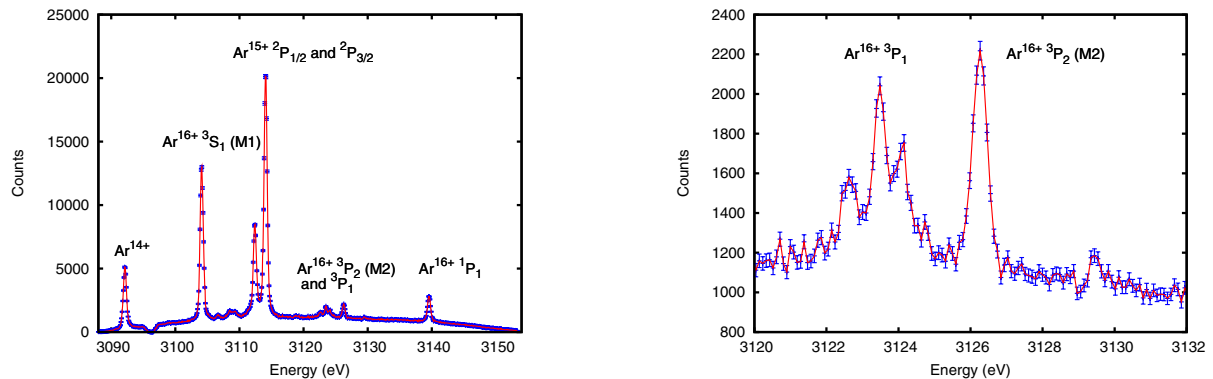
Figure 1. $1s2l \rightarrow 1s^2$ transitions in He-like and Li-like argon spectrum (complete – left, and details of the He-like ^3P_j lines – right) using quartz $(10.\bar{1})$ crystal. Unlabeled lines are 3-electron satellites. This spectrum has been obtained with an integration time of 1 hour.

Table 1. Comparison of the theoretical and experimental values of energy difference, in eV, for some of the $n = 2$ He-like sulphur and argon states. The new results presented here are preliminary.

		Sulphur		Argon	
		$1s2p\ ^3P_2 \rightarrow$ $\rightarrow 1s2s\ ^3S_1$	$1s2p\ ^1P_1 \rightarrow$ $\rightarrow 1s2p\ ^3P_1$	$1s2p\ ^3P_2 \rightarrow$ $\rightarrow 1s2s\ ^3S_1$	$1s2p\ ^1P_1 \rightarrow$ $\rightarrow 1s2p\ ^3P_1$
Drake [13]	(theory)	18.4152	13.4878	22.1455	16.0505
Plante [14]	(theory)	18.4115	13.4857	22.1409	16.0484
Artemyev [15]	(theory)	18.4116(2)	13.4853(2)	22.1413(2)	16.0477(2)
Indelicato [16, 17]	(theory)	18.4117	13.4875	22.1415	16.0505
DeSerio [18]	(UV spectr.)	18.4108(6)			
Schleinkofer [19]	(X-ray spectr.)		13.62(20)		
Kukla [20]	(UV spectr.)			22.1422(6)	
Deslattes [21]	(X-ray spectr.)				16.031(72)
This work	(prel. results)	18.401(27)	13.516(20)	22.127(22)	16.028(11)

are consistent with the theoretical evaluation from different methods: the multiconfiguration Dirac-Fock (Indelicato) [16, 17], the relativistic many-body problem theory (Plante) [14], the unified method (Drake) [13] and a recent calculation for He-like atoms (Artemyev) [15]. The experimental accuracy, however, does not allow to discriminate between the different approaches.

4. Conclusions

We presented new precise energy measurements of transitions in He-like ions obtained with an ECR ion trap newly developed at the Paul Scherrer Institut. The measurements are characterized by an accuracy being about ten times higher than the previous X-ray spectroscopy measurements, but are still affected by systematic effects contributing with about 50% to the total error. These effects are caused by the defocussing of the lines in the detector plane and by the insufficient knowledge of the crystal-detector distance (Fig. 2). At present, we are analyzing all contributions to the line shape, including crystal cut angle (angle between the Bragg plane

and the surface), vertical alignment, defocussing, etc. All the relevant parameters are included in a Monte Carlo simulation for each observed line, that will be used as a basis for line fitting. In addition, the result of the ongoing survey measurement of the mechanical parts will reduce significantly the error originating from the uncertainty in the crystal-detector distance.
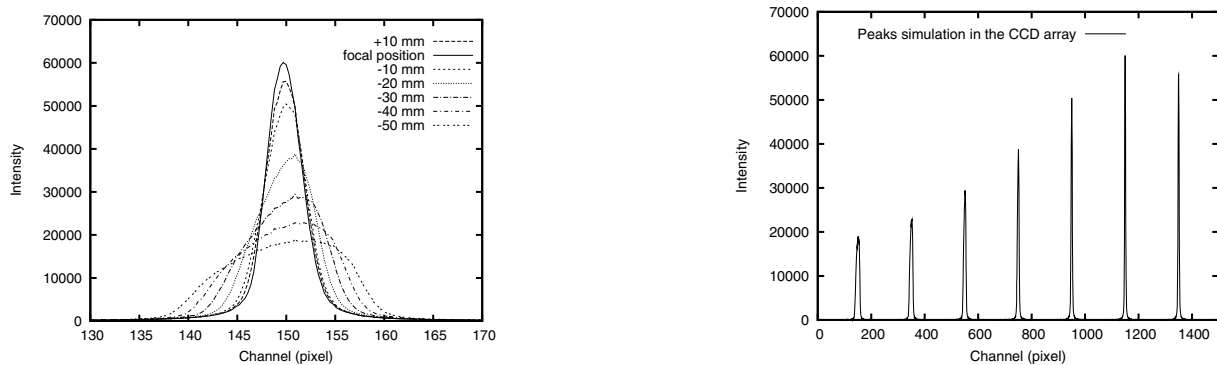

Figure 2. Deformation of the peak on the one-dimensional position spectra as a function of the distance between the detector plane and the Rowland circle – left, and of the position of the reflection in the detector – right (focus position in ch. 1170, 1 ch = 0.09 eV). These profiles have been simulated for X-ray of about 3.1 keV energy and a quartz $(10.\bar{1})$ crystal. The energy decreases with the increase of the channel number.

Acknowledgments

[1] Anagnostopoulos D, Biri S, Fuhrmann H *et al* 2005 *Nucl. Instrum. Meth. A* **545** 217
[2] Pionic Hydrogen Collaboration 1998 *PSI experiment R-98.01* URL http://pihydrogen.web.psi.ch
[3] Bernard C 1996 Ph.D. thesis Université J. Fourier Lyon
[4] Sadeghi N, Nakano T, Trevor D J and Gottscho R A 1991 *J. Appl. Phys.* **70** 2552
[5] Johann H H 1931 *Z. f. Physik* **69** 185
[6] Nelms N, Anagnostopoulos D F, Ayranov O *et al* 2002 *Nucl. Instrum. Meth. A* **484** 419
[7] Indelicato P, Le Bigot E O, Trassinelli M *et al* 2006 *Rev. Sci. Inst.* **77** 043107
[8] Simons L M 1993 *Hyperfine Interactions* **81** 253
[9] Biri S, Simons L and Hitz D 2000 *Rev. Sci. Inst.* **71** 1116
[10] Anagnostopoulos D F, Biri S, Boisbourdain V *et al* 2003 *Nucl. Instrum. Meth. B* **205** 9
[11] Trassinelli M 2005 *Quantum Electrodynamics Tests and X-rays Standards using Pionic Atoms and Highly Charged Ions* Ph.D. thesis Université P. et M. Curie Paris, France URL http://tel.ccsd.cnrs.fr/tel-00067768
[12] Sanchez del Rio M and Dejus J 1998 in *SPIE proceedings* p 3448
[13] Drake G 1988 *Can. J. Phys.* **66** 586
[14] Plante D, Johnson W and Sapirstein J 1994 *Phys. Rev. A* **49** 3519
[15] Artemyev A N, Shabaev V M, Yerokhin V A *et al* *Phys. Rev. A* **71** 062104
[16] Costa A M, Martins M C, Parente F *et al* 2001 *At. Data Nucl. Data Tables* **79** 223
[17] Indelicato P private communication, Indelicato P, Gorveix O and Desclaux J P 1987 *J. Phys. B* **20** 651; Indelicato P 1988 *Nucl. Instrum. Meth. B* **31** 14; Indelicato P 1995 *Phys. Rev. A* **51** 1132; Indelicato P 1996 *Phys. Rev. Lett.* **77** 3323
[18] DeSerio R and Berry H 1981 *Phys. Rev. A* **24** 1872
[19] Schleinkofer L, Bell F, Betz H, Trolman G and Rothermel J 1982 *Phys. Scripta* **25** 917
[20] Kukla K, Livingston A, Suleiman J *et al* 1995 *Phys. Rev. A* **51** 1905
[21] Deslattes R, Beyer H and Folkmann F 1984 *J. Phys. B* **17** L689